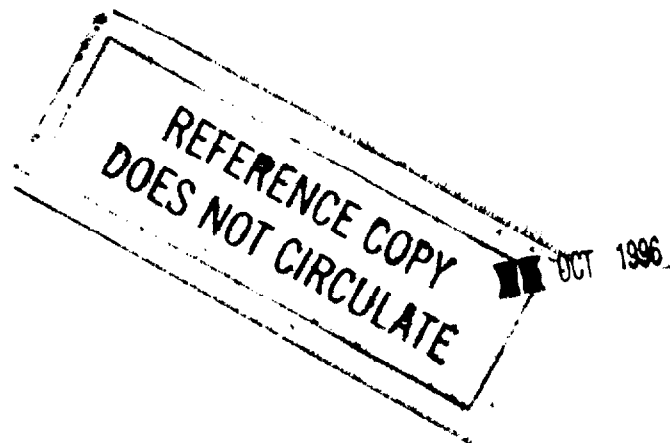


On the Ideality of Using a Step-Function Current in a Metallic Foil to Simulate a Step-Function Heat-Flux Source

Martin S. Miller

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May 1993



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13. ABSTRACT (Maximum 200 words) An exact solution is derived to the one-dimensional, time-dependent, heat-conduction equation for a two-layer, semi-infinite, composite solid with sudden uniform heat generation in the surface layer, no heat transfer through the surface plane, and uniform initial temperature. The interface between the two layers is assumed to have no thermal contact resistance. This solution enables a discussion of the ideality with which a step-function electric current in a metallic foil can generate a step-function heat flux into a contacting semi-infinite solid. Previous measurements of thermal diffusivity (based on the above conditions) have relied on the idealized constant-flux solution for data reduction. It is shown here that the temperature errors in the substrate arising from non-ideality of the constant-flux boundary condition increase with depth into the substrate, foil thickness, and decreasing thermal conductivity/diffusivity of the substrate.				
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1. INTRODUCTION

A number of researchers have reported measurements of thermal transport properties based on the use of an exact solution to the transient heat-conduction equation for the idealized problem of a one-dimensional, semi-infinite solid subjected to a step-function heat flux at the surface (Plummer, Campbell, and Comstock 1962; Harmathy 1964; Steere 1966; Shelley and Huber 1969). Experimentally, this step-function flux is provided by suddenly establishing a constant electric current in a metallic sheet placed in contact with a specimen solid of sufficient thickness as to respond in the same way as a semi-infinite solid for a given data-acquisition time and specimen thermal properties. The ideality of the step-function flux into the specimen solid produced by a step-function current in the metallic sheet has never been thoroughly discussed. Minimizing the heat capacity of the sheet by selecting thin foils has been recognized as desirable by some investigators (Harmathy 1964; Steere 1966) on the basis of the fraction of flux stored in the foil compared to that delivered to the specimen; however, this partitioning of energy bears no straightforward relationship to temperature errors in the interior of the substrate, where the measurements are made. An accurate assessment of the temperature errors there could not be made without solving the transient heat-conduction equation for a two-layer composite solid with uniform heat generation in the surface layer. In this paper we present an exact solution to this problem. We would venture to argue, in fact, that it is only through this solution that one may prove that a constant heat flux into the substrate is the eventual consequence of establishing a steady current in the foil. Additionally, the solution permits the first quantitative assessment of the rate at which this constant-flux boundary condition is established as a function of the foil thickness and the thermal properties of both foil and substrate, such an analysis being of obvious value to the experimentalist.

2. DERIVATION

The mathematical problem is posed as a one-dimensional, semi-infinite, two-region composite solid whose surface is arranged normal to the x coordinate. The surface is located at $x = -d$ and the interface between the two regions at $x = 0$. Properties of the surface layer are denoted by subscript 1, and those of the substrate by subscript 2. The energy-conservation equations in each region are (Carslaw and Jaeger 1959):

$$\rho_1 c_1 \frac{\partial v_1}{\partial t} = \lambda_1 \frac{\partial^2 v_1}{\partial x^2} + A_0 \quad -d < x < 0 \quad (1)$$

$$\rho_2 c_2 \frac{\partial v_2}{\partial t} = \lambda_2 \frac{\partial^2 v_2}{\partial x^2} \quad x > 0 \quad (2)$$

where v is the change in temperature from ambient, t is the time, and A_0 is the rate of heat generated per unit volume in the surface layer. Both equations assume that the total temperature variation is small enough to neglect the temperature dependence of the thermal conductivity λ . The specific heat and mass density are denoted by c and ρ , respectively. Initially, the temperature is uniform, $v = 0$ for all x .

Assuming no contact resistance at $x = 0$, the boundary conditions are

$$\lambda_1 \frac{\partial v_1}{\partial x} = \lambda_2 \frac{\partial v_2}{\partial x} \quad x = 0, \quad t > 0 \quad (3)$$

$$v_1 = v_2 \quad x = 0, \quad t > 0 \quad (4)$$

$$\frac{\partial v_1}{\partial x} = 0 \quad x = -d, \quad t > 0 \quad (5)$$

$$v_2 = 0 \quad x \rightarrow \infty \quad (6)$$

$$v_1 = v_2 = 0 \quad t = 0, \quad \text{all } x \quad (7)$$

For a foil of length L , width W , thickness d , electrical resistance R , conducting a steady current I , the power dissipated per unit volume in the foil is

$$A_0 = \frac{I^2 R}{L W d} \quad (8)$$

Rewriting these equations in terms of the thermal diffusivity, $\alpha = \lambda/(\rho c)$, and applying the Laplace transformation to Equations (1) and (2), one obtains

$$\frac{d^2 V_1}{dx^2} - \left(\frac{p}{\alpha_1} \right)^2 V_1 + \frac{A}{\alpha_1 p} = 0 \quad (9)$$

and

$$\frac{d^2 V_2}{dx^2} - \left(\frac{p}{\alpha_2} \right)^2 V_2 = 0 \quad (10)$$

where the Laplace transform V_i of v_i is defined in terms of the Laplace transform coordinate p as

$$V_i \equiv \int_0^{\infty} v_i e^{-pt} dt \quad i = 1, 2 \quad (11)$$

and

$$A = \frac{I^2 R}{L W d \rho_1 c_1} \quad (12)$$

Together with the transformed boundary equations, these ordinary differential equations have the solutions

$$V_1 = \frac{A}{p^2} - \left(\frac{R_3}{R_1} \right) \frac{1}{p^2} \frac{\left[e^{x \sqrt{\frac{p}{\alpha_1}}} + e^{-(x+2d) \sqrt{\frac{p}{\alpha_1}}} \right]}{\left[1 + \left(\frac{R_2}{R_1} \right) e^{-2d \sqrt{\frac{p}{\alpha_1}}} \right]} \quad (13)$$

$$V_2 = \left\{ \frac{A}{p^2} - \left(\frac{R_3}{R_1} \right) \frac{1}{p^2} \frac{\left[1 + e^{-2d\sqrt{\frac{p}{\alpha_1}}} \right]}{\left[1 + \left(\frac{R_2}{R_1} \right) e^{-2d\sqrt{\frac{p}{\alpha_1}}} \right]} \right\} e^{-x\sqrt{\frac{p}{\alpha_2}}} \quad (14)$$

where

$$R_1 \equiv \left(\frac{\lambda_1}{\sqrt{\alpha_1}} + \frac{\lambda_2}{\sqrt{\alpha_2}} \right) \quad (15)$$

$$R_2 \equiv \left(\frac{\lambda_2}{\sqrt{\alpha_2}} - \frac{\lambda_1}{\sqrt{\alpha_1}} \right) \quad (16)$$

$$R_3 \equiv \frac{\lambda_2 A}{\sqrt{\alpha_2}} \quad (17)$$

We are concerned here primarily with the solution v_2 in the substrate region. Consequently, an inverse transform will be obtained only for this region. The inverse transform for the interior of the foil can be deduced straightforwardly using the same strategy as will be applied to the substrate. If the denominator of the second term in Equation (14) is expanded in a binomial series, the resulting sum may be transformed term by term using known inverse Laplace transforms (Carslaw and Jaeger 1959a). The result is as follows:

$$\begin{aligned}
v_2 = & \left(A - \frac{R_3}{R_1} \right) \left[t \operatorname{erfc} \left(\frac{x}{2\sqrt{\alpha_2 t}} \right) - x \sqrt{\frac{t}{\alpha_2}} \operatorname{ierfc} \left(\frac{x}{2\sqrt{\alpha_2 t}} \right) \right] \\
& - \frac{R_3 t}{R_1} \operatorname{erfc} \left(\frac{2d\sqrt{\alpha_2} + x\sqrt{\alpha_1}}{2\sqrt{\alpha_1 \alpha_2 t}} \right) + \frac{R_3 \sqrt{t}}{R_1} \left(\frac{2d\sqrt{\alpha_2} + x\sqrt{\alpha_1}}{\sqrt{\alpha_1 \alpha_2}} \right) \operatorname{ierfc} \left(\frac{2d\sqrt{\alpha_2} + x\sqrt{\alpha_1}}{2\sqrt{\alpha_1 \alpha_2 t}} \right) \\
& - \frac{R_3}{R_1} \sum_{n=1}^{\infty} (-1)^n \left(\frac{R_2}{R_1} \right)^n \left[t \operatorname{erfc} \left(\frac{2nd\sqrt{\alpha_2} + x\sqrt{\alpha_1}}{2\sqrt{\alpha_1 \alpha_2 t}} \right) - \left(\frac{2nd\sqrt{\alpha_2} + x\sqrt{\alpha_1}}{\sqrt{\alpha_1 \alpha_2}} \right) \sqrt{t} \operatorname{ierfc} \left(\frac{2nd\sqrt{\alpha_2} + x\sqrt{\alpha_1}}{2\sqrt{\alpha_1 \alpha_2 t}} \right) \right] \\
& - \frac{R_3}{R_1} \sum_{n=1}^{\infty} (-1)^n \left(\frac{R_2}{R_1} \right)^n \left[t \operatorname{erfc} \left(\frac{2(n+1)d\sqrt{\alpha_2} + x\sqrt{\alpha_1}}{2\sqrt{\alpha_1 \alpha_2 t}} \right) - \left(\frac{2(n+1)d\sqrt{\alpha_2} + x\sqrt{\alpha_1}}{\sqrt{\alpha_1 \alpha_2}} \right) \sqrt{t} \operatorname{ierfc} \left(\frac{2(n+1)d\sqrt{\alpha_2} + x\sqrt{\alpha_1}}{2\sqrt{\alpha_1 \alpha_2 t}} \right) \right] \quad (18)
\end{aligned}$$

3. APPLICATION

With this solution (Equation 18) one may examine the transient heat flux into a semi-infinite solid produced by a step-function current in a metallic surface layer. For this purpose we consider two substrate materials, polyethylene and fused quartz, which effectively cover the range of properties of materials studied in the cited references. All of those studies employed constantan foils, each adopting a different thickness, 0.127 mm (Plummer, Campbell, and Comstock 1962), 0.025 mm (Harmathy 1964), and 0.0025 mm (Steere 1966). The experimental arrangement in each of these studies consists of a thick slab of specimen (effectively infinitely thick relative to the data-acquisition time) on either side of the foil. All authors assumed that a step-function current established in the foil produces a step-function heat flux into the semi-infinite solid on either side of the foil. The step-function-flux solution (v_{SFF}) for this case is given by (Carslaw and Jaeger 1959b)

$$v_{SFF} = \frac{A_0 d \sqrt{\alpha_2 t}}{\lambda_2} \operatorname{ierfc} \frac{x}{2\sqrt{\alpha_2 t}} \quad (19)$$

This solution is the same as for the case of a single semi-infinite solid bounded by a foil which is insulated on its other side, but with half the flux of the latter. Our 2-layer, semi-infinite solution found

above can also describe the infinite-composite-solid case if the two semi-infinite regions are of the same material. By symmetry the temperature gradient at the midplane of the foil in the infinite composite solid is zero, which is the same boundary condition used in the derivation of Equation (18). All other boundary conditions are the same. Thus the solution for the infinite composite solid is the same as that for a semi-infinite composite solid of half the conducting-layer thickness.

In the case of an idealized step-function heat flux (Equation 19), the flux into one of the semi-infinite solids is simply $A_0 d/2$ for all times after $t = 0$ (Carslaw and Jeager 1959). For the case of the finite foil thickness (Equation 18), the flux at any time may be found from the solution Equation (18) by taking the partial derivative of v_2 with respect to x evaluated at $x = 0$ and multiplying the result by the thermal conductivity of the substrate λ_2 . The quality of the step-function-flux assumption is then easily assessed by normalizing the heat flux for the finite-foil case to that of the idealized case. Thus the ideality of the step-function flux assumption may be judged by the shortfall of this ratio from unity. Figures 1a and 1b show the results for polyethylene and fused-quartz substrates, respectively. First of all, these figures confirm the fact that establishing a step-function current in a finite-thickness foil will indeed ultimately produce a constant flux into the substrate if one waits long enough. This may seem an intuitively obvious result, but can only be proved using the exact solution for the finite-foil case (Equation 18). Secondly, the step-function-flux idealization is clearly compromised to a greater extent for the lower-conductivity materials and for thicker foils (as expected). Experiment durations ranged from about 4 s (Steere 1966) to 420 s (Harmathy 1964). Figures 1a and 1b warn that experiments of short data-acquisition times must pay close attention to using foils of sufficient thinness, particularly with low-conductivity specimens.

The basic data of the cited thermal diffusivity experiments consist of temperature measurements, at a known distance from the foil into the substrate, as a function of time. In Figures 2a and 2b the ratio of the exact solution (Equation 18) to the idealized solution (Equation 19) is plotted to illustrate the net effect of compromises in the step-function-flux idealization on the temperature at various depths in the substrate. At 5 s temperature errors of almost 50% are possible. Even at times as long as 50 s, errors as large as 10% can occur in low-conductivity materials. Both Harmathy (1964) and Steere (1966) attempted to assess the importance of the finite heat capacity of the foil by demonstrating that the heat per unit area stored in the foil after some time t is small (for their respective experimental conditions) compared to the total heat generated by the foil per unit area after t (including that heat lost to the substrate). However, in order to compute the heat stored in the foil, both authors determined the temperature of the foil after t by means of the idealized step-function-flux solution (Equation 19). While the step-function-flux solution

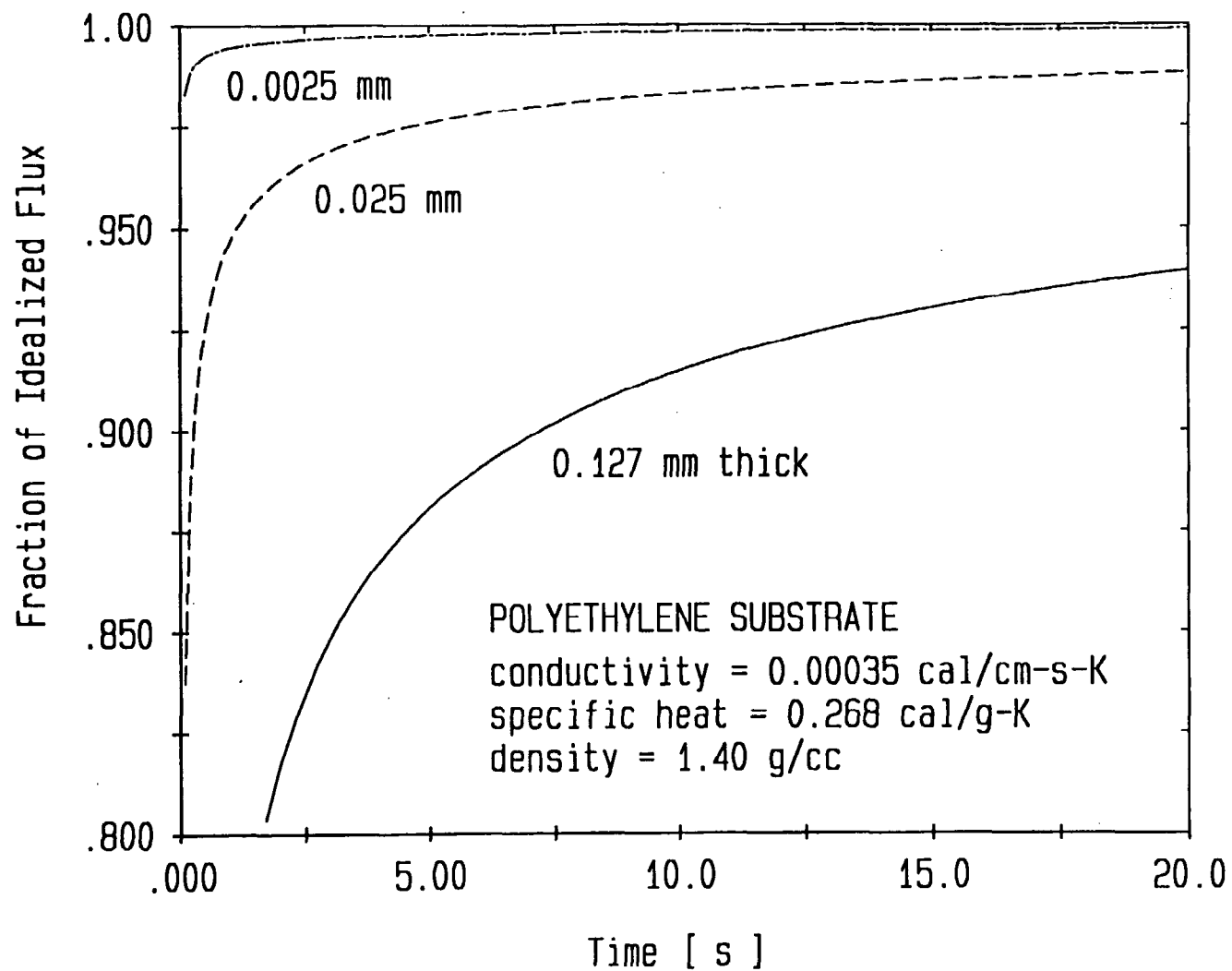


Figure 1a. Ideality of the step-function-flux boundary condition for constantan foils of various thicknesses on a substrate of polyethylene.

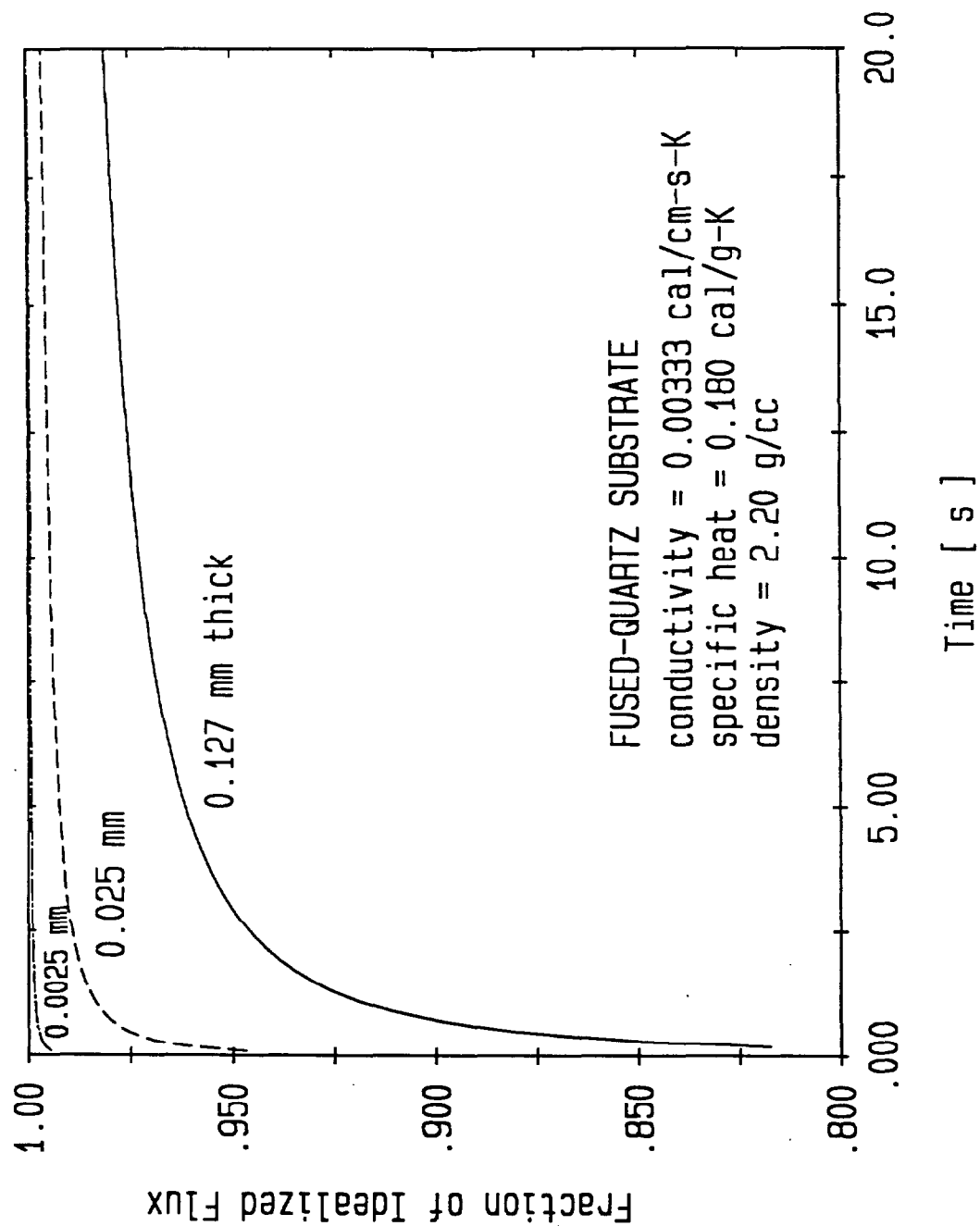


Figure 1b. Ideality of the step-function-flux boundary condition for constantan foils of various thicknesses on a substrate of fused quartz.

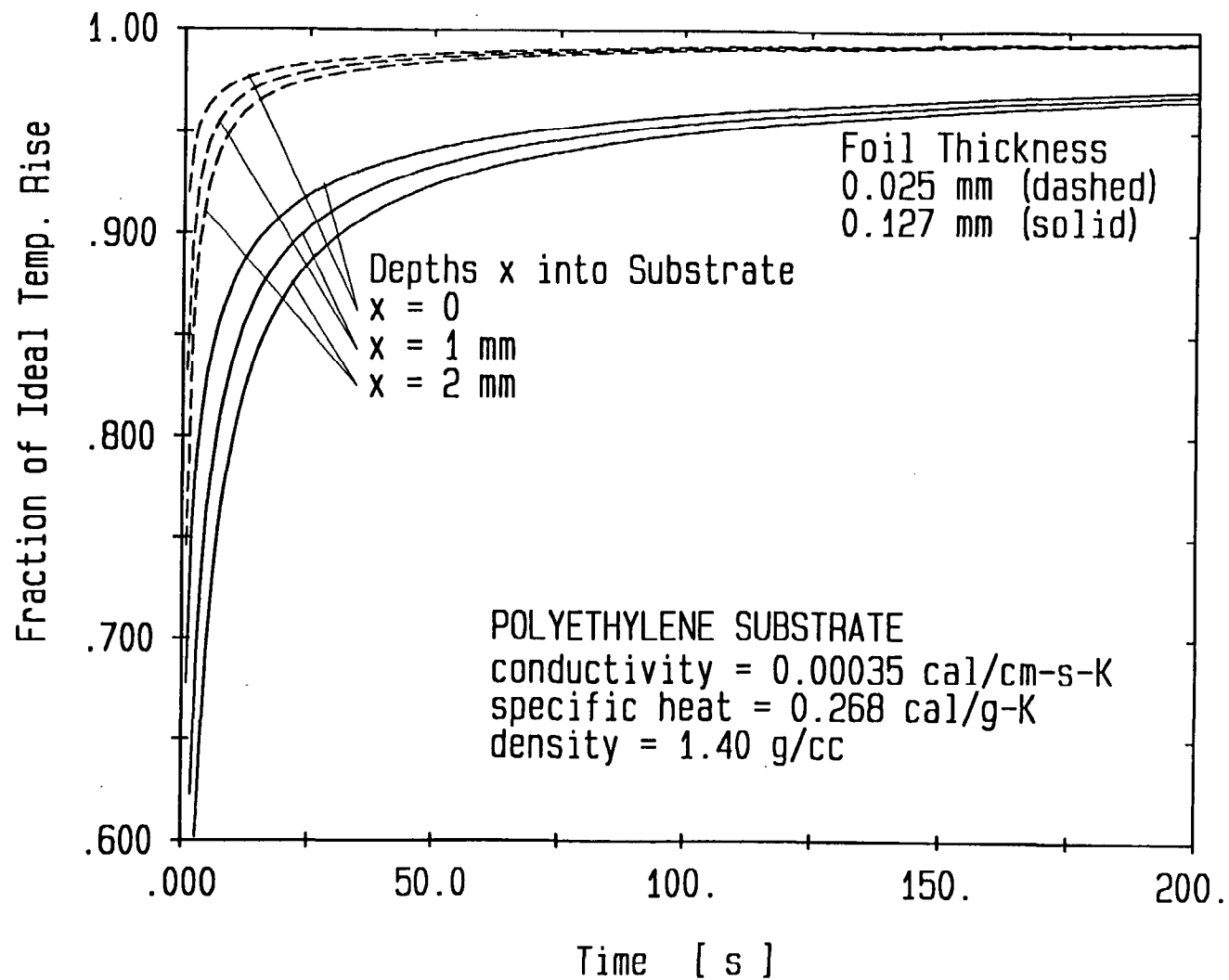


Figure 2a. Temperature errors at various substrate depths for two constantan-foil thicknesses resulting from non-ideality of constant-flux boundary condition - polyethylene substrate.

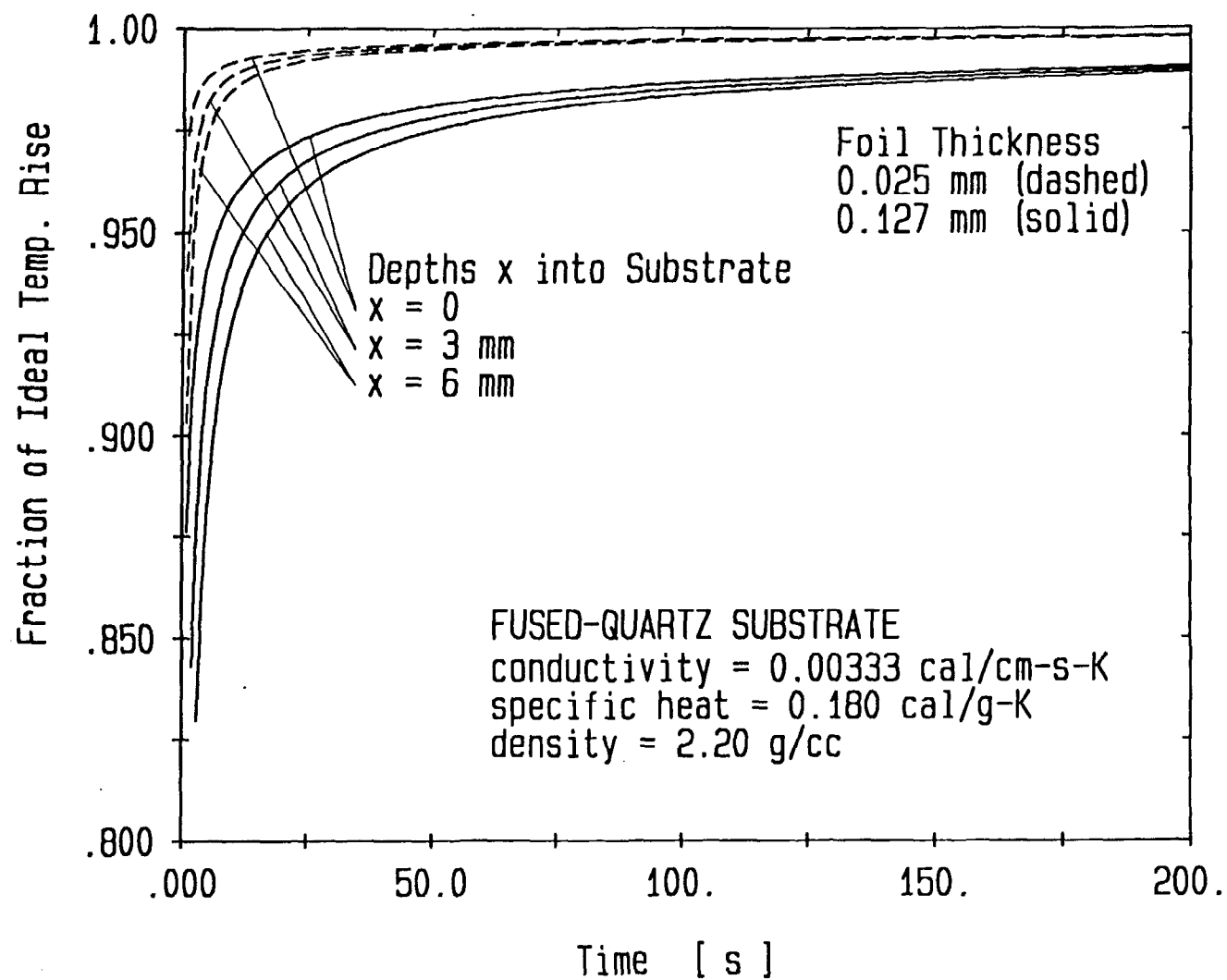


Figure 2b. Temperature errors at various substrate depths for two constantan-foil thicknesses resulting from non-ideality of constant-flux boundary condition - fused-quartz substrate.

(Equation 19) does lead to an upper limit to the foil temperature, the resultant energy partitioning between foil and substrate bears no fixed relation to the temperature errors in the interior of the substrate, where the temperature is really analyzed. Using Equation (18) we find that the ratio of exact to idealized temperature can be greater than or less than the ratio of heat absorbed by the substrate to the total heat generated, depending on the depth considered. Though their method of analyzing the error due to finite foil thickness is not rigorously justified, it does turn out to give an order-of-magnitude estimate of the error for their particular circumstances.

Applying Harmathy's (1964) data-reduction technique and his choice of a 420-s data-acquisition period, we find that for a polyethylene specimen his use of a 0.025-mm foil results in a 1.2% underestimate in the thermal diffusivity. Had he used a 0.127-mm foil (as did Plummer, Campbell, and Comstock [1962]), the diffusivity would be underestimated by 5.5%. Steere's (1966) much shorter data-acquisition period of 4 s would result in a 5.2% underestimate in diffusivity for a 0.025-mm foil and a 17.6% underestimate using a 0.127-mm foil. Steere actually used a 0.0025-mm foil, resulting in a finite-foil-thickness error of only 0.5%. These errors in diffusivity values, though significant in some cases, are smaller than the errors in the temperature data themselves. The mitigating effect is due to the fact that Harmathy's analysis relies on *ratios* of temperatures at different times rather than the absolute temperatures. That the ratios of temperatures at different times (at a given distance from the surface) are more accurate than the temperatures themselves may be seen from Figures 2a and 2b.

4. CONCLUSION

In summary an exact solution has been presented to the time-dependent, one-dimensional heat conduction equation for a two-layer, semi-infinite composite solid, initially at uniform temperature, whose surface layer is subjected to a step-function electric current flow. It was shown that the solution may also be applied to a three-layer infinite composite solid (foil sandwiched between two semi-infinite solids of the same material) simply by using half the real foil thickness in the semi-infinite solution. The three-layer infinite composite solid has previously been used by a number of authors to provide a step-function heat-flux boundary condition in experiments to measure thermal diffusivity of insulator materials. The new mathematical solution enables a discussion of the ideality with which the step-function heat flux is achieved. It was shown how the quality of the idealization depends on the thickness of the current-carrying layer, the thermal diffusivity and conductivity of the substrate, and the depth in the substrate at which the temperature is measured.

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LIST OF SYMBOLS

- c = specific heat (subscript 1 foil, 2 substrate)
- d = thickness of foil
- I = current in surface layer (constantan foil)
- L = length of foil ribbon
- p = Laplace transform coordinate
- R = electrical resistance of foil
- t = time
- v = temperature difference from initial value
- V = Laplace transform of v
- w = width of foil ribbon
- x = spatial variable normal to surface
- α = thermal diffusivity (subscript 1 foil, 2 substrate)
- λ = thermal conductivity (subscript 1 foil, 2 substrate)
- ρ = density (subscript 1 foil, 2 substrate)

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